

## Article

# Enhancing Digital Innovation Ecosystem Resilience through the Interplay of Organizational, Technological, and Environmental Factors: A Study of 31 Provinces in China Using NCA and fsQCA

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**Abstract:** Digital innovation ecosystems are currently experiencing a period of growth and are navigating uncertain environments. Improving resilience is an important prerequisite for ensuring sustainable developments. This study, based on the technology, organization, and environment (TOE) framework, examines the impact of multilevel antecedent conditions on digital innovation ecosystem resilience using data from 31 Chinese provinces. By applying a necessary condition analysis (NCA) and fuzzy-set qualitative comparative analysis (fsQCA), this study reveals complex causal relationships between five antecedents at the “technology–organization–environment” levels and digital innovation ecosystem resilience, along with the improvement paths of digital innovation ecosystem resilience. The results show the following: Firstly, individual antecedent conditions alone do not constitute necessary conditions for high or non-high digital innovation ecosystem resilience. Secondly, there are five configuration paths leading to high digital innovation ecosystem resilience, namely, a digital technology-enabled organization–environment-driven type (H1a), an organization–environment dual-wheel-driven type (H1b), a digital technology-led environment-driven type (H2), a technology–organization–environment trilateral type (H3), and a pressure–organization-driven type (H4). Thirdly, three configuration paths result in non-high digital innovation ecosystem resilience, exhibiting an asymmetric relationship with paths associated with the configuration paths of high digital innovation ecosystem resilience. Finally, potential substitution relationships exist among antecedent conditions at the technological, organizational, and environmental levels.

**Keywords:** digital innovation ecosystem; resilience; TOE framework; necessary condition analysis; fuzzy-set qualitative comparative analysis



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## 1. Introduction

A digital innovation ecosystem (DIE) is cultivated through the interplay of competition and collaboration among subjects engaged in digital innovation [1]. As an exclusive byproduct of the digital economy era, a digital innovation ecosystem exhibits distinct features characterized by the digitization of innovation elements, the virtualization of subjects, and the establishment of ecological relationships among subjects. These attributes effectively contribute to the advancement of organizations and industries [2]. A 2019 report by Gartner drew attention to the significant market share held by Alibaba Cloud in the cloud computing industry of the Asia–Pacific region, underscoring the role of DIEs in bolstering core digital technologies [3]. A DIE not only stimulates technological advancement but also facilitates the digital transformation of conventional sectors. Examples include the development of the “Yulianwang” platform in the fisheries and the “DiDi” platform in travel services, both supported by a robust digital innovation ecosystem [4]. The stable operation of DIEs is crucial for enhancing digital innovation capabilities [5]. However,

being a nascent product of the digital economy era, digital innovation ecosystems currently find themselves in a phase of rapid growth, accompanied by an inherent imperfection in their resilience to risks. In the VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) era, DIES face unpredictable ‘black swan’ or ‘gray rhino’ events, such as the challenges that Huawei encountered due to trade sanctions, including technology blockades and disruptions in the supply of chips [6]. These situations emphasize the necessity for DIES to enhance their resilience to withstand risks posed by the external turbulent environment; to address diverse challenges; and to sustainably evolve to higher levels, ensuring stability and capitalizing on opportunities in the digital economy. The resilience of DIES not only serves as the premise for sustainable development of a digital innovation ecosystem but also manifests as the result of its dynamic evolution. As a premise, establishing and sustaining high resilience to withstand external shocks is significant for a digital innovation ecosystem to promote high-quality development [7]. As a result, the resilience of a digital innovation ecosystem is subject to a diverse array of influencing factors [8].

Regarding research methodologies, prior studies have primarily delved into antecedent conditions and their “net effect” on digital innovation ecosystem resilience through theoretical analyses and case studies. However, there is a lack of studies that provide a comprehensive and holistic framework that incorporates antecedent conditions at different levels and explores their intricate interactions. This gap becomes apparent when looking at the limited emphasis on necessity logic in current research. This lack of focus on the varying levels of necessity makes it challenging to thoroughly understand the complex causal relationships that influence the resilience of digital innovation ecosystems.

As a complex adaptive system [5], a digital innovation ecosystem constitutes an intricate combination of diverse technologies, organizations, environmental factors, and other elements [9]. Consequently, this study aims to employ the technological, organizational, and environmental (TOE) framework, utilizing a necessary condition analysis with a focus on necessity logic, along with a fuzzy-set qualitative comparative analysis that accentuates sufficient logic. The objective is to comprehensively investigate the influence of antecedent conditions and configurations at three levels—technology, organization, and environment—on digital innovation ecosystem resilience. Specifically, this paper seeks to address the following inquiries: Whether and to what extent are there necessary conditions for high digital innovation ecosystem resilience? Which configuration paths will lead to high/non-high digital innovation ecosystem resilience? Are there substitution relations among different antecedent conditions?

## 2. Literature Review and Theoretical Framework

### 2.1. Digital Innovation Ecosystem Resilience

Resilience, originally rooted in engineering [10], found an application in ecology through the work of Holling [11], who defined it as the capacity of an ecosystem to return to a stable state after suffering a disruption. Over time, resilience evolved from its engineering origins to ecological resilience, eventually advancing towards evolutionary resilience [8]. The study of resilience has transcended its initial confines within natural ecology; has gradually expanded into the realm of social science; and has undergone widespread adaptation across diverse disciplines [10], spanning micro and meso levels, including organizations and communities [12]. In recent years, the concept of resilience was introduced into the field of digital innovation ecosystems [8,13].

The theme of DIE resilience stems from research on DIES. Currently, research into DIES predominantly focuses on their conceptualization [1,2,5,9], evolution [1,9], and governance [2]. In the era of VUCA, resilience has emerged as a critical factor for ensuring the sustainable development of a DIE, and scholars have also started to concentrate on resilience [8,13]. Based on the idea of a socioecological system, DIE resilience is seen as the ability to recover or progress in the face of disturbances, leveraging unique digital technology functions, system adaptations, and transformability [10,12]. Resilience encompasses four dimensions: diversity, evolution, fluidity, and buffering [8]. However, there are

a few studies directly addressing the topic of “digital innovation ecosystem resilience”, especially in terms of antecedents.

The existing body of research on the antecedent conditions of DIE resilience can be categorized into several primary domains. These encompass studies that center on the theme of “digital innovation ecosystem resilience”, inquiries regarding “innovation ecosystem resilience” within the context of a high-tech industry, and investigations concentrating on specific dimensions of digital innovation ecosystem resilience. Notably, a limited number of studies, exemplified by Yang et al. [8], directly delved into the overarching theme of “digital innovation ecosystem resilience”, exploring the impact of governance niches on DIE resilience from the governance perspective. Chen and Cai suggested that some factors, such as urbanization, human capital, digital industrialization, and industrial structure, play positive roles in enhancing digital innovation ecosystem resilience, particularly at the level of urbanization [13]. However, most research examines how various factors influence these specific dimensions. Typically, such research investigates three primary levels: technology, organization, and environment. At the technological level, studies explore how digital technology facilitates a more efficient sharing of resources [14], thereby enhancing system fluidity. The organizational level encompasses factors such as the diversity of innovation subjects, inter-subject relations, and resource management. The presence of diverse entities improves system resilience and fault tolerance [15], while the dynamics between competitive and cooperative entities facilitate the flow of resources [16], thereby enhancing the fluidity and buffering capacities of the system. Enterprises, equipped with abundant resources, can effectively navigate crises and pressures [17], thereby ensuring the stable operation of the system. From an environmental perspective, research investigates how external factors and innovation environments impact resilience. A changing external environment accelerates the circulation of resources [16], and effectively navigating this uncertainty is crucial for resilience [17]. A conducive innovation environment serves as a catalyst for innovation activities, fostering collaborative interactions among subjects [18], and, consequently, it influences the buffering capabilities of a digital innovation ecosystem.

The reviewed literature has paved the way for studying the resilience of digital innovation ecosystems. However, this emerging field suffers from a lack of empirical research, which is both limited and fragmented. Specifically, this field faces a notable lack of comprehensive frameworks, hindering a detailed exploration of the complex causal relationships among various factors and the resilience of digital innovation ecosystems. Therefore, this paper utilizes the TOE (technology, organization, and environment) framework as an inclusive research structure to integrate factors from technological, organizational, and environmental perspectives. By adopting this method, a theoretical model is developed to explore the impact of these factors at different levels, along with their interactions, on the resilience of digital innovation ecosystems.

## 2.2. Research Framework

This paper aims to consolidate dispersed research on the antecedent conditions of digital innovation ecosystem resilience by employing the TOE framework. Rooted in technology application scenarios, the TOE framework offers a comprehensive analytical structure at three levels: technology, organization, and environment [19]. The technological level explores the attributes of technology and its alignment with organizational structures. The organizational level covers considerations such as organizational scale, structure, and internal resources [20]. Meanwhile, the environmental level examines the impact of external factors on organizations, encompassing aspects like institutional and market environments. The application of TOE framework is motivated by several key considerations. Firstly, the technological level of the TOE framework effectively captures the distinct digital characteristics of a digital innovation ecosystem. Secondly, the dimensions of technology, organization, and environment within the TOE framework constitute fundamental elements of complex systems, enabling a clearer understanding of the mechanisms that underpin the interplay of multiple factors in such systems. The high resilience of a digital

innovation ecosystem is perceived as a consequence of the synergistic interplay among technological, organizational, and environmental factors, rather than the outcome of any singular antecedent condition. This perspective aligns with the core principles of the TOE framework. Lastly, the TOE framework's notable flexibility and operational adaptability make it a popular choice in relevant research. For example, Li et al. utilized the TOE framework to explore improvement paths for the development capability of high-tech industries' innovation ecosystems [21]. Hence, by integrating previous research on digital innovation ecosystem resilience with the TOE framework, this paper identifies and selects antecedent factors at the technological, organizational, and environmental levels.

### 2.3. Model Construction

#### 2.3.1. Technological Level

The application of digital technology establishes the foundation of the technological infrastructure essential for an innovation ecosystem, acting as a critical prerequisite for its digitalization. The distinctive attributes of digital technology contribute to the enhancement of digital innovation ecosystem resilience or its dimensions from multiple perspectives. For instance, the openness and integrative nature of digital technology foster recurrent interactions among ecosystem participants, facilitating resource acquisition and improving utilization rates. Such interactions aid in risk mitigation [22] and fortify overall resilience. Furthermore, the application of digital technology within a digital innovation ecosystem serves to broaden the "coverage" of information transmission channels and extends their "shelf life", promoting information sharing among participants [14], consequently augmenting the fluidity of a digital innovation ecosystem. However, it is noteworthy that certain studies highlight potential drawbacks associated with the application of digital technology, such as challenges in subject collaboration and process control within a digital innovation ecosystem [2]. These challenges may, in turn, undermine resilience. Therefore, the impact of the digital technology application on digital innovation ecosystem resilience remains subject to further investigation and clarification.

#### 2.3.2. Organizational Level

Serving as the linchpin in the design and construction of digital ecosystems [23], the organization constitutes a confluence of diverse resources [24]. Human resources emerge as a pivotal determinant for achieving high resilience within the system [17]. An ample reservoir of human resources facilitates a swift absorption and integration of information, enabling the organization to flexibly adapt to changes in the external environment [25], in turn fostering the system's healthy and sustainable development. Adequate R&D investments lay a robust material foundation for the organization to surmount challenges [17], enhancing innovation output and bolstering digital innovation ecosystem resilience from an evolutionary standpoint. For instance, within the artificial intelligence innovation ecosystem, the cultivation of highly qualified talents accelerates information flow and stimulates the "metabolism" of the system [26]. R&D investments contribute to elevating the value-creation level of the digital innovation ecosystem [27], expediting resource allocation efficiency and thereby augmenting the fluidity and evolution of the system. As posited above, this paper contends that human resources and R&D investments exert a discernible impact on digital innovation ecosystem resilience, and it designates them as antecedent conditions at the organizational level.

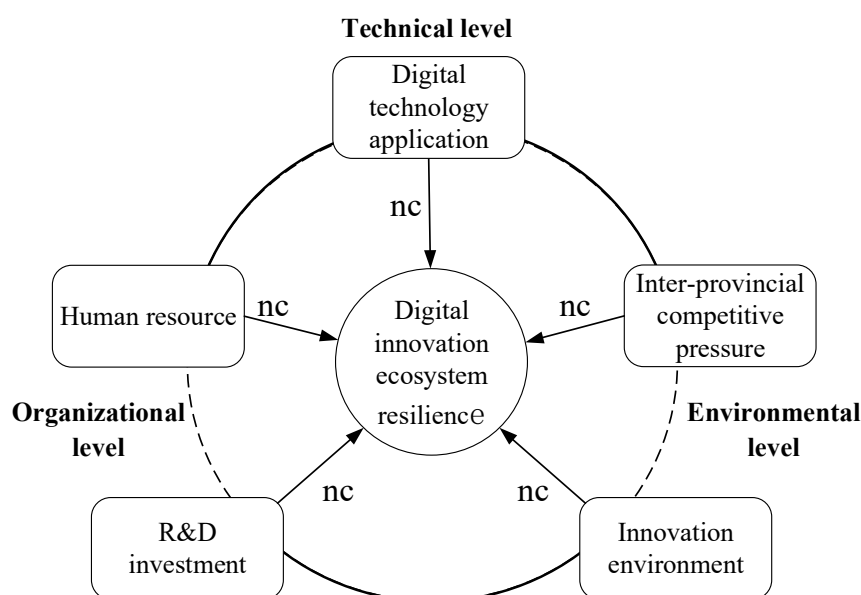
#### 2.3.3. Environmental Level

The innovation environment, an external milieu upon which innovation subjects depend for their sustenance [28], represents a pivotal component of an innovation ecosystem. An open and inclusive innovation environment serves to stimulate the collision of ideas and facilitates the exchange of experiences among subjects [29]. This, in turn, energizes innovation vitality, fostering the effective allocation of resources and enhancing the fluidity and evolution of a digital innovation ecosystem. Empirical evidence from previous studies

have indicated that, by catalyzing innovation inputs to improve innovation outputs [28], a favorable innovation environment can contribute to resilience, particularly in terms of fluidity and evolution. A digital innovation ecosystem exhibits regional characteristics [8], and given the provincial scope of this paper's research, inter-provincial competitive pressure emerges as a significant environmental factor [20]. This pressure manifests in resource competition from neighboring provinces, prompting provincial governments to stimulate enthusiasm [30] and to proactively formulate decision-making plans to develop digital innovation ecosystem resilience based on existing resource endowments. Concurrently, competitive pressure propels innovation subjects to actively learn and absorb new knowledge [25], facilitating the iteration of resources and thereby enhancing system evolution. Consequently, both the innovation environment and inter-provincial competitive pressure may exert influences on digital innovation ecosystem resilience.

#### 2.3.4. Research Model

Prior research has elucidated the impact of specific antecedent conditions on the resilience of digital innovation ecosystems or their dimensions, to a certain extent. Drawing from the complex-system perspective [31], innovation ecosystem resilience is posited as the outcome of synergistic effects stemming from antecedent conditions across multiple levels. Focusing solely on the net effect of a factor at an individual level may lead to a "one-sided" understanding. For instance, an innovation environment's infrastructure constitutes both the hardware and software support for digital technology [18], thereby providing the resource endowment essential for the application of digital technology [32]. The diverse knowledge and culture introduced by a varied human resource pool contribute to the enhancement of the innovation environment [29]. Organizations adeptly leverage both internal and external environments to bolster the application of digital technology. Anchored in the configuration perspective and holistic theory, this paper formulates a research model (Figure 1), delving into the necessity causation among five antecedent conditions at the technological, organizational, and environmental levels and elucidating how these antecedent conditions interconnect and align to influence digital innovation ecosystem resilience.



**Figure 1.** Research model. “nc” indicates the exploration of the necessary relationship between antecedent conditions and the result [33]. Solid lines establish connections between antecedent conditions across different levels, while dotted lines establish connections between antecedent conditions at the same level.



### 3. Research Design

#### 3.1. Research Methodology

The fsQCA method explores the configuration effects of multiple antecedent conditions and their intricate causal relationships with the outcome [34]. The reasons for selecting fsQCA are as follows: (1) Its asymmetric nature [35] allows fsQCA to identify the asymmetric relationship between paths leading to high and non-high digital innovation ecosystem resilience. (2) FsQCA enables a comprehensive analysis of both necessity and sufficiency relationships [34,35], aiding in elucidating the complex causal interplay between antecedent conditions and their combinations on digital innovation ecosystem resilience. (3) Given that a digital innovation ecosystem is a complex system, where factors influencing its resilience do not exist independently, fsQCA, based on set theory, can discern multiple paths associated with the result [36]. This approach is not affected by nested relationships among levels [34], providing insights into the intricate interplay of factors across the technological, organizational, and environmental levels, aligning well with the TOE framework. (4) FsQCA is not constrained by the number of case samples [37]. With 31 cases considered in this study, it falls within the medium-scale case sample range, making it suitable for fsQCA.

The NCA method, proposed by Dul [38], serves as a complementary research method to fsQCA to test the necessary logic of antecedent conditions on the outcome, effectively addressing the limitations of fsQCA in necessity analyses. NCA not only determines whether an antecedent condition is necessary but also quantitatively reveals the degree of necessity [38,39]. Necessary conditions for an NCA analysis can exist at various levels, such as the individual, enterprise, or national levels [38]. A digital innovation ecosystem, characterized by a complex linkage and a match of diverse elements, fits within the TOE framework and encompasses various antecedent conditions across multiple levels, making it applicable to NCA. Consequently, this paper employs both fsQCA and NCA for an empirical analysis.

#### 3.2. Samples and Data

This study utilizes digital innovation ecosystems from 31 provinces (including provinces, municipalities, and autonomous regions) in China as case samples. The selection of provinces as the unit of analysis is grounded in two primary considerations: First, provincial governments not only directly implement the national overarching strategy for digital innovation but also formulate and implement pertinent policies within their respective provinces, assuming a pivotal “connecting” role. This “connecting” role makes the research findings practically significant and broadly applicable. Second, provinces are key regional economic entities with well-defined economic-activity boundaries and comprehensive statistical data [8], making this selection consistent with the fsQCA case-selection criteria of “case similarity” and “maximum heterogeneity between cases” [37].

In accordance with the prevailing empirical research on digital innovation ecosystems, this study focuses on the high-tech industry [8,15,17]. In the era of industrialization and information, the high-tech industry emerges as a key driver of regional competitiveness and is an impetus for related industries. It exerts a substantial technological spillover effect and showcases significant innovation capabilities [40]. Notably, the “Manufacture of Electronic Equipment and Communication Equipment” and the “Manufacture of Computers and Office Equipment” are highlighted for their high degree of marketization and industry concentration, representing core sectors of the digital economy known for early openness and frequent digital-innovation activities [8]. These industries are designated as representative examples of high-tech industries, in alignment with existing research [8].

Regarding data sources, in recognizing the time-lag effect in the impact of factor inputs on digital innovation ecosystem resilience, this paper establishes a lag time of one year. Antecedent conditions from the year 2019 and outcomes from the year 2020 are selected for analysis. This temporal approach allows for a more nuanced understanding of the delayed influence of factor inputs on the resilience of a digital innovation ecosystem.

### 3.3. Measurement and Calibration

Digital innovation ecosystem resilience, as measured by Yang Wei et al. [8], includes four dimensions: diversity, evolution, fluidity, and buffering. This paper builds upon Yang's methodology, while also addressing missing data for certain provinces.

A digital technology application is evaluated using the digital financial inclusion index, following the research of Li Shuina [41]. The digital financial inclusion index comprises three primary indicators: the breadth of coverage, the depth of use, and the degree of digitization. The entropy method is applied to determine the weights for these indicators.

Human resources are quantified through the average years of schooling, based on the work of Yang Ligao et al. [42].

An R&D investment is gauged using the intensity of the R&D investment metric, as identified by Zhu Guilong et al.'s [43] research.

The innovation environment is assessed with data from the comprehensive index of the innovation environment in China's regional innovation capability, which includes five indicators, the innovation infrastructure, the market environment, labor quality, the financial environment, and the entrepreneurship level, following the research of Wang Chongfeng et al. [44].

Inter-provincial competitive pressure: Based on the research of Chen Shuangying et al. [30], this paper uses the digital economy integration index of adjacent provinces as a metric. This metric calculates the average value of the traditional industry and the digital economy integration index of adjacent provinces.

To analyze the data, this paper adopts the direct calibration method, aligning with established methodologies in previous studies [30]. The calibration anchors for full membership, the crossover point, and full non-membership are determined by the 75%, 50%, and 25% quantiles of each variable, respectively. To mitigate the challenging attribution phenomenon associated with a case membership degree of 0.5, a minor adjustment is made by subtracting 0.001 from the fuzzy-set membership score of 0.5, resulting in an adjusted value of 0.499 [37]. Table 1 provides a detailed overview of the description, calibration procedure, and data sources for each variable.

**Table 1.** Description, calibration, and data sources of variables.

Variable	Description	Full Membership	Crossover Point	Full Non-Membership	Data Sources
Digital technology application	Breadth of coverage, depth of use, and degree of digitization of digital financial inclusion index in 2019	357.403	335.267	310.492	The Peking University Digital Financial Inclusion Index of China (2011–2020)
Human resource	The average years of schooling in 2019	12.189	11.909	11.367	China statistical yearbook (2020)
R&D investment	The intensity of R&D investments in 2019	2.100	1.610	0.950	China statistical yearbook (2020)
Innovation environment	The score of the innovation environment in 2019	26.870	21.990	19.120	Evaluation Report on Regional Innovation Ability in China (2019)
Inter-provincial competitive pressure	The average value of the traditional industry and the digital economy integration index of adjacent provinces in 2019	36.150	30.500	25.867	Digital economic development index of China (2019)
Digital innovation ecosystem resilience	The score of the digital innovation ecosystem resilience in 2020	173,613.455	95,722.222	42,611.645	China statistical yearbook on high technology industry (2021); China statistical yearbook on science and technology (2021); China statistical yearbook (2021); Report of Key Laboratory in China (2016)

## 4. Empirical Analysis

### 4.1. Analysis of Necessary Conditions

NCA and fsQCA employ distinct standards and logic for necessary condition analyses. Combining these methods enhances the accuracy of analyzing variations in the necessity degree of antecedent conditions [39,45]. In the context of NCA, a necessary condition signifies the specific level of X required for the specific level of Y, providing insights into the extent to which X is a requisite for Y. However, fsQCA only assesses whether X is a necessary condition for Y in kind [38,39], potentially yielding a lower count of necessary conditions compared to NCA. However, these two approaches do not inherently conflict [38,45]. Following the approach employed by Du Yunzhou et al. [31], this paper initiates an analysis with NCA for a necessity assessment. Subsequently, fsQCA is applied to test and serves as the judgment basis, ensuring a comprehensive evaluation of the necessity of antecedent conditions in the context of digital innovation ecosystem resilience.

The NCA analysis results were generated using the R studio software (2022.07.2-576) and R language (4.1.3). The initiation of an NCA analysis involves the examination of a scatter diagram. A void in the upper-left corner of the scatter diagram suggests the potential existence of necessary conditions [46]. The ceiling line serves as the reference for the NCA assessment, with several key parameters calculated by the R studio software (2022.07.2-576), including the scope, ceiling zone, and effect size. The effect size, a crucial metric, represents the minimum level of necessary conditions for a specific outcome, falling within the range of 0 to 1. Effect sizes are categorized as follows:  $0 < d < 0.1$  indicates a “small effect,”  $0.1 \leq d < 0.3$  corresponds to a “medium effect,” and  $0.3 \leq d < 0.5$  characterizes a “large effect” [46]. To establish whether an antecedent condition is deemed necessary, two conditions must be met: the effect size (d) of the antecedent condition should be no less than 0.1, and the Monte Carlo Simulations of Permutation Tests should yield a significant effect size ( $p < 0.05$ ) [31]. The results of the necessity analysis conducted through NCA are presented in Table 2.

**Table 2.** Necessity analysis results based on the NCA method.

Antecedent Condition	Approach	Accuracy	Upper-Left Area	Scope	Effect Size (d)	p Value
Digital technology application	CR	90.3%	0.248	0.98	<b>0.253</b>	<b>0.000</b>
	CE	100%	0.243	0.98	0.248	0.000
Human resource	CR	90.3%	0.065	0.99	0.065	0.019
	CE	100%	0.017	0.99	0.017	0.111
R&D investment	CR	87.1%	0.356	0.99	<b>0.360</b>	<b>0.000</b>
	CE	100%	0.328	0.99	0.331	0.000
Innovation environment	CR	87.1%	0.237	0.99	<b>0.240</b>	<b>0.000</b>
	CE	100%	0.129	0.99	0.130	0.000
Inter-provincial competitive pressure	CR	96.8%	0.017	0.99	0.017	0.258
	CE	100%	0.030	0.99	0.030	0.166

Notes: CR refers to ceiling regression, and CE refers to ceiling envelopment. CR is apt for continuous variables, aligning with the data characteristics in this paper. CE is well-suited for variables featuring less than five categories. Both are applied in this research to ensure a comprehensive comparison of result robustness. The p value was obtained by a permutation test with a re-sample count of 10,000 in the NCA. The bolded indicate that the numerical value of this indicator meets the selection criteria of necessary conditions for NCA analysis.

Table 2 reveals that, in accordance with the criteria of effect size ( $d > 0.1$ ) and  $p < 0.05$ , digital technology application, R&D investment, and innovation environment may be necessary conditions for digital innovation ecosystem resilience. Table 3 presents the results of a bottleneck-level analysis. The bottleneck level (%), as depicted in this table, signifies the minimum level of antecedent conditions essential to attain the maximum observed range of results [31].



**Table 3.** Analysis of bottleneck level (%) based on the NCA method.

Digital Innovation Ecosystem Resilience	Digital Technology Application	Human Resource	R&D Investment	Innovation Environment	Inter-Provincial Competitive Pressure
0	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	0.2
20	4.6	NN	6.9	NN	0.6
30	11.3	NN	16.3	NN	1.0
40	18.0	NN	25.8	NN	1.3
50	24.7	NN	35.2	6.8	1.7
60	31.5	4.6	44.6	23.2	2.1
70	38.2	10.2	54.1	39.5	2.5
80	44.9	15.9	63.5	55.8	2.9
90	51.6	21.5	72.9	72.2	3.2
100	58.3	27.1	82.3	88.5	3.6

Note: NN = unnecessary.

As delineated in Table 3, to attain a 90% digital innovation ecosystem resilience, the requisite levels include 51.6% digital technology application, 21.5% human resource, 72.9% R&D investment, 72.2% innovation environment, and 3.2% inter-provincial competitive pressure.

Subsequently, this study employs fsQCA to validate the outcomes of the NCA necessity analysis. In fsQCA, an antecedent condition is deemed necessary for the result if the consistency level exceeds 0.9 [37]. The results of the fsQCA necessity analysis are shown in Table 4.

**Table 4.** Necessity analysis results based on the fsQCA method.

Antecedent Condition	High Digital Innovation Ecosystem Resilience		Non-High Digital Innovation Ecosystem Resilience	
	Consistency	Coverage	Consistency	Coverage
Digital technology application	0.824	0.856	0.272	0.290
~Digital technology application	0.317	0.298	0.866	0.835
Human resource	0.619	0.561	0.539	0.502
~Human resource	0.451	0.488	0.528	0.587
R&D investment	0.883	0.822	0.275	0.263
~R&D investment	0.208	0.218	0.813	0.877
Innovation environment	0.807	0.767	0.357	0.348
~Innovation environment	0.314	0.322	0.761	0.802
Inter-provincial competitive pressure	0.714	0.693	0.395	0.394
~Inter-provincial competitive pressure	0.375	0.376	0.693	0.713

Note: the notation “~” means the absence of the variable.

According to Table 4 and on the basis of judgment [31], it is evident that there is no necessary condition for attaining high or non-high resilience in a digital innovation ecosystem.

#### 4.2. Configuration Analysis

The configuration analysis of high/non-high digital innovation ecosystem resilience is conducted by using the fsQCA3.0 software. To ensure robustness, the case frequency setting retained 75% or more of the observed cases. A validation of the conditional configuration's consistency in accordance with fuzzy-set theory [37] is essential, especially considering the small and medium sample sizes. Following previous research [31], this paper set the case threshold to 1, the original consistency threshold to 0.8, and the PRI consistency value threshold to 0.7. The detailed results are presented in Table 5.

**Table 5.** Configuration analysis results.

Antecedent Condition	High Digital Innovation Ecosystem Resilience					Non-High Digital Innovation Ecosystem Resilience		
	H1a	H1b	H2	H3	H4	NH1a	NH1b	NH1c
Digital technology application	●		●	●	⊗	⊗	⊗	⊗
Human resource		⊗	⊗	⊗	●	⊗	⊗	
R&D investment	●	●		●	●	⊗	⊗	⊗
Innovation environment	●	●	●		⊗	⊗	⊗	⊗
Inter-provincial competitive pressure		⊗	●	●	●	⊗		⊗
Consistency	0.921	0.942	0.954	0.997	0.968	0.914	0.925	0.957
Raw coverage	0.683	0.179	0.205	0.249	0.119	0.353	0.414	0.521
Unique coverage	0.398	0.022	0.026	0.061	0.013	0.053	0.115	0.222
Overall consistency			0.914				0.941	
Overall coverage			0.827				0.690	

Notes: ● indicates the presence of a core condition; ⊗ indicates the absence of a core condition; ● indicates the presence of a peripheral condition; ⊗ indicates the absence of a peripheral condition; the blank area indicates “dispensable”.

#### 4.2.1. Configurations of High Digital Innovation Ecosystem Resilience

Table 5 reveals five configuration paths contributing to high digital innovation ecosystem resilience. Notably, configurations H1a and H1b share identical core conditions, establishing them as second-order-equivalent configurations [31]. Each configuration exhibits a consistency surpassing 0.8, affirming their effectiveness in achieving high digital innovation ecosystem resilience.

Adhering to the guidelines for configuration naming [31], this study designates the five configurations leading to high resilience as follows: the digital technology-enabled organization–environment-driven type (H1a), the organization–environment dual-wheel-driven type (H1b), the digital technology-led environment-driven type (H2), the technology–organization–environment trilateral type (H3), and the pressure–organization-driven type (H4). Table 6 provides a comparative analysis of configurations associated with high digital innovation ecosystem resilience, encompassing the configuration names, views, explanations, and case diagrams.

**Table 6.** Comparative analysis of configurations of high digital innovation ecosystem resilience. The bold texts indicate that the conditions exist or absent as core conditions.

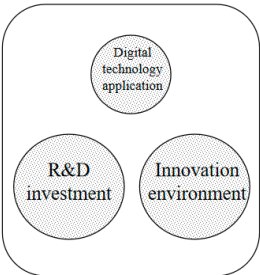
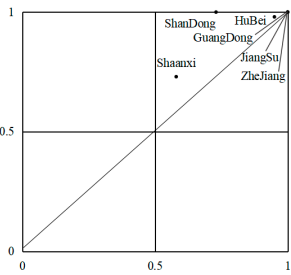
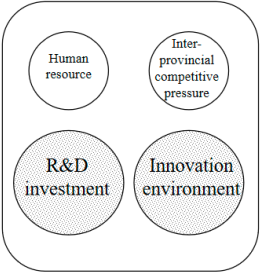
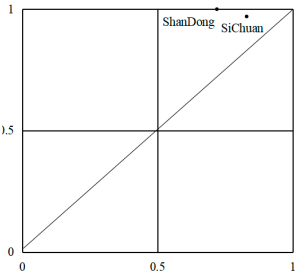
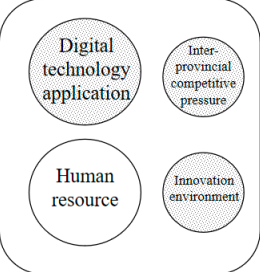
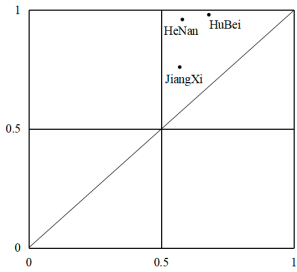
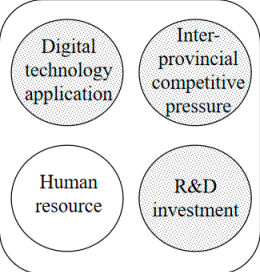
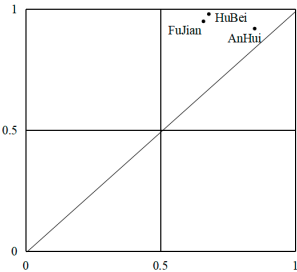
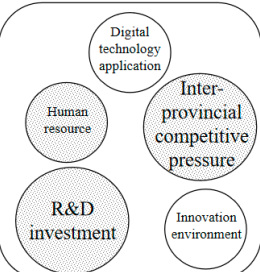
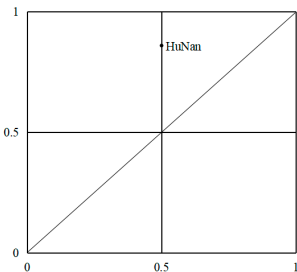
Configuration Name	Configuration View	Configuration Explanation	Case Diagram
H1a digital technology-enabled organization–environment-driven type		Digital technology application <b>*R&amp;D investment*</b> <b>Innovation environment</b> → high digital innovation ecosystem resilience	

Table 6. Cont.

Configuration Name	Configuration View	Configuration Explanation	Case Diagram
H1b organization–environment dual-wheel-driven type		$\sim$ Human resource* <b>R&amp;D investment</b> * <b>Innovation environment</b> * $\sim$ Inter-provincial competitive pressure→high digital innovation ecosystem resilience	
H2 digital technology-led environment-driven type		<b>Digital technology application</b> * $\sim$ Human resource* <b>Innovation environment</b> *Inter-provincial competitive pressure→high digital innovation ecosystem resilience	
H3 technology–organization– environment trilateral type		Digital technology application* $\sim$ Human resource* <b>R&amp;D investment</b> *Inter-provincial competitive pressure→high digital innovation ecosystem resilience	
H4 pressure–organization– driven type		$\sim$ Digital technology application*Human resource* <b>R&amp;D investment</b> * $\sim$ Innovation environment* <b>Inter-provincial competitive pressure</b> →high digital innovation ecosystem resilience	

H1a is of the digital technology-enabled organization–environment-driven type. In the H1a configuration, R&D investment and innovation environment exist as core conditions, and digital technology application exists as a peripheral condition. This configuration underscores that a high digital innovation ecosystem resilience is achievable when systems exhibit substantial R&D investments, fostered by a favorable innovation environment, and supported by digital technology. R&D investments play a pivotal role in ensuring a constant influx of funds for innovation subjects, thereby promoting technological progress, augmenting innovation capacity, and fortifying innovation resilience [47]. The innovation environment, providing a physical space for inter-subject collaboration and essential knowledge and resources, facilitates the construction of an innovation network. This, in turn, aids in the diffusion of digital innovation, elevating innovation outputs and ensuring the vitality of a digital innovation ecosystem. A digital technology application enables seamless communication across temporal and spatial boundaries, fostering a virtuous cycle and the

intelligent matching of innovative resources. This optimization enhances the allocation of resources within a digital innovation ecosystem, thereby bolstering overall resilience.

To enhance the practical value of a case analysis in alignment with QCA standards [31], Guangdong Province, represented within configuration H1a, was selected for a detailed examination. In 2019, Guangdong demonstrated prominence in R&D investments, ranking first in China, with R&D intensity placing among the top five nationally, surpassing the country's average. This province has strategically fortified its innovation infrastructure, exemplified by initiatives like the provincial laboratory, through consistent increases in R&D investments. Such substantial investments solidified the hardware foundation of the innovation environment. Simultaneously, the government proactively introduced and adjusted relevant laws and regulations to overcome innovation bottlenecks, actively fostering the creation of an optimal innovation environment [48]. Key enterprises, including Huawei, underscored the significance of digital technology applications in urban constructions. They have driven smart-city developments by integrating digital technologies such as cloud computing, GIS, and AI [49]. The concerted efforts in digital technology applications, coupled with a high intensity of R&D investments and a conducive innovation environment, positioned Guangdong Province to cultivate a robust digital innovation ecosystem in the digital economy era. This resilience not only effectively withstands external shocks but also contributes to the province's overall capacity to adapt and thrive.

H1b is of the organization–environment dual-wheel-driven type. In the H1b configuration, R&D investment and innovation environment exist as core conditions, while human resource and inter-provincial competitive pressure are absent as peripheral conditions. This configuration posits that, even in the absence of robust human resources and competitive pressure, systems can attain high digital innovation ecosystem resilience, provided the innovation environment is optimal, and R&D investments are intensive. Provinces experiencing lower inter-provincial competitive pressure encounter reduced environmental uncertainties, enhancing their ability to secure necessary external resources. Consequently, subjects in such provinces can efficiently utilize resources, maintaining a lower cost of harmonious cooperation [50]. An ideal innovation environment can furnish ample funds to support high-intensity innovation activities or to attract additional innovative talents to compensate for human-resource deficiencies. Substantial funds stemming from R&D investments serve to attract innovative talents and to facilitate resource aggregation, fostering a collaboration between the industry, universities, and research institutes. This collaborative environment, characterized by redundant resources and a complex structure, contributes to the diversity and buffering of system resilience.

Following the case-selection criteria outlined in QCA [31], Sichuan Province was chosen for examination, as it uniquely fits the criteria without overlapping with other configurations. In 2019, Sichuan Province supported the development of 51 big-data and 34 artificial-intelligence projects, leveraging its hydropower and other resources to enhance digital infrastructure [51] and to foster an innovation-friendly environment. According to the Statistical Bulletin of Science and Technology Funding Investment in Sichuan Province for 2019, the province witnessed a 0.15% increase in R&D investment intensity compared to the previous year, reaching a historic high. Notably, Chengdu, serving as a robust economic “backbone” and a key hub within the Chengdu Plain Economic Zone, saw R&D investments rise by 17.3% and 15.4% [52], respectively. Positioned as a linchpin of the western-development strategy, Sichuan Province boasts a solid economic foundation and favorable innovation environment. Additionally, the relatively lower level of digital development in neighboring provinces partially alleviates survival pressures on Sichuan's digital innovation ecosystem, facilitating system optimization and resilience development.

H2 is of the digital technology-led environment-driven type. In the H2 configuration, digital technology application exists as a core condition, inter-provincial competitive pressure and innovation environment exist as peripheral conditions, and human resource absents as a core condition. This configuration underscores that, despite challenges such as inadequate human resources and heightened inter-provincial competitive pressure, the

meticulous attention given to digital technology applications and innovation-environment constructions can yield high digital innovation ecosystem resilience. The application of digital technology strengthens connections between subjects and enhances resource-matching efficiency [53], effectively augmenting system fluidity. An effective innovation environment integrates the necessary resources, fostering a synergistic innovation dynamic [54] and thereby fortifying system buffering. Within the context of a substantial inter-provincial competition, this configuration has a dual impact. On the one hand, competitive pressure propels enterprises to employ digital technology for problem identification and swift resource balancing to adapt to external changes and impacts [55]. On the other hand, confronted with intense competitive pressure, the system continually refines itself, contributing to the attainment of high resilience.

Following the case-selection criteria of the H1a and H1b configurations, Henan Province serves as an illustrative example. In 2019, this province actively supported the establishment of the Huawei Kunpeng computing industrial ecosystem, leveraging 5G and artificial intelligence technologies to penetrate the core of the technology industry. Zhengzhou, the provincial capital, developed an “urban brain” infrastructure, including a data center and big-data platform, to address information silos using digital technologies [56]. The “Henan Innovation and Entrepreneurship Development Report 2020” highlighted cities in Henan Province creating innovation and entrepreneurship incubation platforms, enhancing market competitiveness and openness and continually improving the innovation environment in response to the “double innovation” policy. The widespread adoption of digital technology and the enhancement of the innovation environment fostered the development of the digital innovation ecosystem in Henan Province. Additionally, the “China Regional Innovation Capability Evaluation Report 2019” indicates stable and improved indicators in Henan Province, with a notable 315.34% growth rate in the enterprise technology transaction volume. Henan Province’s proximity to six provinces with higher developmental levels amplifies competitive pressure, prompting effective measures to overcome human-resource constraints and to facilitate the healthy development of the digital innovation ecosystem alongside the adoption of digital technology and favorable innovation conditions.

H3 is of the technology–organization–environment trilateral type. In the H3 configuration, digital technology application, R&D investment, and inter-provincial competitive pressure exist as core conditions, and human resource absents as a core condition. This configuration illustrates that, through the concerted impact of widespread digital technology applications, high-intensity R&D investments, and intense inter-provincial competitive pressure, a system can achieve high digital innovation ecosystem resilience, even in the absence of human resources in certain provinces. Digital technology, when widely applied, not only facilitates cost-effective high-output data elements but also enhances communication and collaboration between subjects [5]. This, in turn, promotes efficient resource flow and iterative updates and elevates the fluidity and evolution of the digital innovation ecosystem. The heightened uncertainty induced by competitive pressure motivates subjects to establish an interest alliance of “many hands make light work,” integrating existing resources to swiftly address shocks. Technology is employed innovatively to overcome challenges such as resource constraints brought about by competition [57]. R&D investments play a crucial enabling role; a higher R&D investment intensity correlates with greater progress in digital technology, thereby enhancing the digital innovation ecosystem’s competitive standing [47].

Adhering to the case-selection criteria outlined above, Anhui Province serves as an exemplary case. This province strongly advocates for the application of digital technology, fostering an environment where digital enterprises collaborate and share resources to attract developers through open platforms and data-rich environments, thereby nurturing a collaborative ecosystem for digital technology applications and developments [58]. Anhui Province prioritizes research and development as a key investment area, allocating 2.23% of its expenditure to this domain in 2019. Situated in the Yangtze River Delta integration region



and neighboring provinces, such as Zhejiang and Jiangsu, which boast a rapid digital economy growth, Anhui faces significant competitive pressure [59]. Consequently, this province actively learns from neighboring provinces' innovative practices to cultivate and advance its digital innovation ecosystem. Leveraging the interplay of inter-provincial competitive pressure, R&D investments, and digital technology applications, Anhui Province strives to foster sustainable and resilient developments within its digital innovation ecosystem, capable of withstanding external shocks.

H4 is of the pressure–organization-driven type. In the H4 configuration, R&D investment and inter-provincial competitive pressure exist as core conditions, human resource exists as a peripheral condition, and digital technology application and innovation environment are absent as peripheral conditions. This configuration elucidates that provinces with deficient digital technology applications and innovation environments can achieve high digital innovation ecosystem resilience by ensuring an ample supply of talents, funds, and competitive pressure. R&D personnel, possessing creativity and subjective initiative, emerge as crucial supporters and subjects of digital innovation, independently allocating funds and other resources within the system [60]. This compensates, to a certain extent, for resource shortages stemming from a suboptimal innovation environment. A high intensity of R&D investments plays a dual role: it ensures a robust knowledge stock, providing solutions for challenges, such as low innovation efficiency, resulting from insufficient digital technology applications [43]. Concurrently, competitive pressure acts as a catalyst for innovation activities, fostering frequent imitation and learning among innovation subjects [61]. This dynamic enhances the utilization rate and flow of resources, ultimately fortifying system resilience.

Hunan Province stands as the sole case corresponding to the H4 configuration. According to the China Statistical Yearbook, the R&D investment intensity in Hunan Province rose from 1.81% in 2018 to 1.98%, with the China Regional Innovation Capability Evaluation Report 2019 noting an increase in R&D investments from CNY 5.6 billion in 2018 to CNY 7.049 billion in 2019, representing a growth rate of 25.88%. Situated adjacent to Guangdong Province, a leader in the national digital economy scale, and Guizhou Province, housing data centers of digital enterprise giants like Apple, Hunan Province faces competitive pressures in its digital innovation ecosystem developments. Benefitting from abundant educational resources, institutions such as the Central South University and Hunan University continually supply high-quality talent for digital innovation. The synergy of human-resource encouragement, research and development investments, and competitive pressure stimulation accelerates resource flow efficiency, mitigating barriers within digital innovation ecosystems. This facilitates the “healing” process post external shocks, thereby enhancing system resilience.

Through a comparative analysis of the five configurations, H1a emerges with the highest raw coverage and unique coverage, signifying its pivotal role as the primary pathway to attaining high digital innovation ecosystem resilience. It shows that high digital innovation ecosystem resilience results from the synergistic interaction of multiple factors, such as technology-enabled organizations and environments. Furthermore, this study identifies R&D investment as a core condition in four configurations, underscoring its universal significance. This observation aligns with the findings of pertinent studies [27], reinforcing the positive impact of R&D investments on various dimensions of digital innovation ecosystem resilience. Additionally, digital technology applications are featured in three configurations, providing empirical support for previous research conclusions that highlight its positive influence on dimensions of digital innovation ecosystem resilience [14].

#### 4.2.2. Configurations of Non-High Digital Innovation Ecosystem Resilience

Table 5 delineates three configuration paths leading to non-high digital innovation ecosystem resilience, all characterized by the absence of digital technology applications, R&D investments, and a conducive innovation environment as core conditions. These configurations are identified as second-order configurations, in accordance with estab-

lished criteria [31]. Configuration NH1a underscores that neglecting digital technology applications, coupled with a dearth of resources and inadequate support from a favorable innovation environment, along with the absence of inter-provincial competition promotion, results in non-high digital innovation ecosystem resilience. The NH1b configuration elucidates that poor digital technology applications, an unfavorable innovation environment, insufficient funds, and a scarcity of talents contribute to non-high resilience in the digital innovation ecosystem. The NH1c configuration highlights that provinces experiencing low inter-provincial competitive pressure exhibit non-high digital innovation ecosystem resilience when lacking R&D funding support, neglecting innovation-environment constructions and ignoring digital technology applications.

Through a horizontal comparison of the three configurations, it becomes evident that the NH1c configuration stands out with a higher raw coverage and unique coverage compared to the other configurations. This indicates that NH1c is the primary pathway leading to the generation of non-high digital innovation ecosystem resilience. A commonality across all configurations is the lack of digital technology application and R&D investment, both playing pivotal roles. This underscores that, in the digital economy era, deficiencies in digital technology applications and inadequate R&D investments significantly impede the enhancement of resilience in the digital innovation ecosystem.

#### 4.3. Robustness Tests

In this study, consistent with the approach proposed by Zhang Ming and Du Yunzhou [37], two methods were employed for robustness testing. Firstly, the PRI consistency threshold is elevated from 0.7 to 0.75. Secondly, the calibration anchors of sample data for antecedent conditions and outcomes were modified to 80%, 50%, and 20% quantiles. The results of the robustness tests are presented in Table 7.

Table 7. Robustness tests.

Antecedent Condition	Configurations of High Digital Innovation Ecosystem Resilience									
	Increasing the PRI Consistency Threshold					Changing the Calibration Anchors of Data				
	H1a *	H1b *	H2 *	H3 *	H4 *	H1a **	H1b **	H2 **	H3 **	H4 **
Digital technology application	●		●	●	⊗	●		●	●	⊗
Human resource		⊗	⊗	⊗	●		⊗	⊗	⊗	●
R&D investment	●	●		●	●	●	●		●	●
Innovation environment	●	●	●		⊗	●	●	●		⊗
Inter-provincial competitive pressure		⊗	●	●	●		⊗	●	●	●
Consistency	0.921	0.942	0.954	0.997	0.968	0.936	0.953	0.941	1.000	0.992
Raw coverage	0.683	0.179	0.205	0.249	0.119	0.663	0.209	0.217	0.262	0.157
Unique coverage	0.398	0.022	0.026	0.061	0.013	0.362	0.016	0.021	0.052	0.011
Overall consistency			0.914					0.920		
Overall coverage			0.827					0.791		

Notes: ● indicates the presence of a core condition; ⊗ indicates the absence of a core condition; ● indicates the presence of a peripheral condition; ⊗ indicates the absence of a peripheral condition; the blank area indicates “dispensable”. The superscript \*/\*\* indicates two robustness test configuration results.

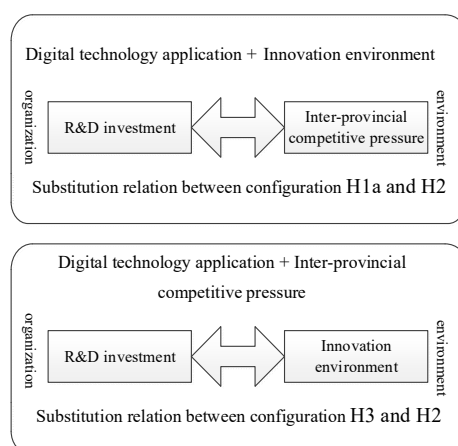
Following the robustness evaluation standard of fsQCA [37], an examination of Table 7 reveals that the new configurations resulting from an increased PRI consistency threshold align consistently with the original configurations, with no alterations observed in consistency and coverage. The overall consistency and coverage levels meet the stipulated criteria, affirming the robustness of the research findings. In the new configurations derived from changes in calibration anchors, the overall consistency of the configurations sees a marginal increase from 0.914 to 0.920, while the overall coverage level experiences a slight reduction from 0.827 to 0.791. Despite these adjustments, the new configurations remain

in alignment with the original configurations, further underscoring the robust nature of the results.

#### 4.4. Analysis of Substitution Relations

Building upon the insights derived from Tan Haibo et al.'s research [20], this study extends the analysis to identify potential substitution relationships among antecedent conditions at the technological, organizational, and environmental levels. Through a comparative examination of five configurations associated with high digital innovation ecosystem resilience, three distinct types of substitution relations emerge.

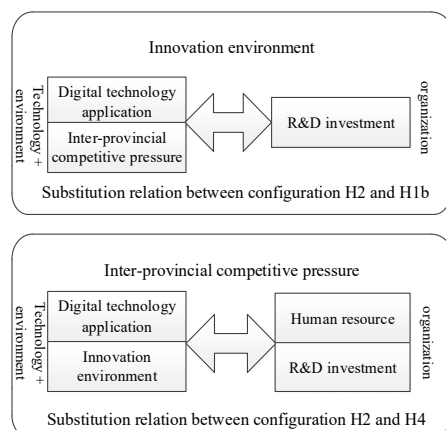
Type 1 is the substitution relationship between antecedent conditions at the organizational level and environmental level, as shown in Figure 2.



**Figure 2.** Substitutions between organization and the environment.

In a comparison between configurations H1a and H2, it is evident that provinces characterized by widespread applications of digital technology and a favorable innovation environment exhibit a substitution relationship between R&D investments (organizational level) and inter-provincial competitive pressures (environmental level). Similarly, a contrast between the H3 and H2 configurations reveals that in provinces with widespread digital technology applications and significant competitive pressures, a substitution relationship exists between R&D investments (organizational level) and the innovation environment (environmental level).

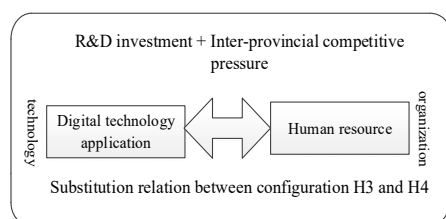
Type 2 is the substitution relation between the combination of antecedent conditions at the technological and environmental levels and the antecedent conditions at the organizational level, as shown in Figure 3.



**Figure 3.** Substitutions between technology, environment, and organization.

Comparing the H2 and H1b configurations reveals that, in provinces with a favorable innovation environment, the combination of digital technology applications (technological level) and inter-provincial competitive pressures (environmental level) can serve as a substitute for R&D investments (organizational level). Similarly, an examination of the H2 and H4 configurations illustrates that in provinces experiencing a significant competitive pressure, the combination of digital technology applications (technological level) and innovation environments (environmental level) exhibits a substitution relationship with the combination of human resources (organizational level) and R&D investments (organizational level).

Type 3 is the substitution relation between the antecedent conditions at the technological level and the organizational level, as shown in Figure 4.



**Figure 4.** Substitution between technology and organization.

In a comparison between the H3 and H4 configurations, it becomes evident that in provinces characterized by a high intensity of R&D investments and competitive pressures, there exists a substitution relationship between digital technology applications (technological level) and human resources (organizational level).

The potential substitution of antecedents at the technological, organizational, and environmental levels implies the overarching significance of R&D investments. This prominence is underscored by the fact that, within a given innovation environment, the impact of the combination of digital technology applications and inter-provincial competitive pressures can be supplanted by the isolated antecedent condition of R&D investments, as depicted in the upper part of Figure 3. This substitution is possible because, even in the absence of competitive pressures, a high intensity of R&D investments can propel technological developments in relevant industries within a digital innovation ecosystem, subsequently enhancing innovation capabilities [47]. This, in turn, achieves an effect equivalent to the combination of digital technology applications and competitive pressures. The substitution relationships between the organizational and environmental levels, as illustrated in Figure 2, further underscore the practical significance of R&D investments in augmenting digital innovation ecosystem resilience. Given that the innovation environment and inter-provincial competitive pressure are objective conditions that are challenging to rapidly improve and considering R&D investments as a subjective resource endowment, the controllability of R&D investments allows provinces to promptly elevate their intensity, thus superseding environmental factors that are difficult to optimize and enhancing digital innovation ecosystem resilience.

## 5. Discussion, Conclusions, Recommendations, and Limitations

### 5.1. General Discussion

This study contributes to the evolving discourse on digital innovation ecosystems (DIEs) in the face of adversity. By applying the technological, organizational, and environmental (TOE) framework, this paper tried to dissect the underlying conditions that foster resilience. We discovered that the strength of DIEs lies in the symbiotic relationship between technological, organizational, and environmental factors. Together, these elements empower ecosystems to adapt, survive, and flourish, even when challenges arise.

Digital innovation ecosystems (DIEs) constitute complex adaptive systems [5], wherein resilience manifests through a system's ability to withstand and recover from disturbances. This resilience is not merely about survival; it entails a dynamic evolution that leverages

digital technology functions, system adaptations, and transformability [10,12]. Our study identifies the various configurations of resilience of DIES, from those driven by digital technology and the organization–environment to those propelled by organizational pressure. These configurations reveal the need for a balanced approach that merges technological advancements, organizational resources, and environmental adaptability.

Moreover, the pivotal role of R&D investments across multiple configurations in our study underscores their universal significance in bolstering various dimensions of DIE resilience, aligning with previous research [27]. This indicates a direct correlation between the infusion of resources into innovation and the enhanced capacity of DIES to navigate through the complexities and uncertainties of the digital economy era.

Additionally, we found that substitution relationships exist among the antecedent conditions at the technological, organizational, and environmental levels, adding depth to our understanding of DIE resilience. Notably, the paramount importance of R&D investments indicates that within a supportive innovation environment, the effects of digital technology applications and competitive pressures can be effectively offset by strategic R&D investments. This points to the fact that the flexibility of DIES must navigate resource limitations and optimize resilience through strategic planning.

Therefore, our study offers essential insights for policymakers and stakeholders within digital innovation ecosystems, stressing the importance of R&D investments, strategic digital technology applications, and the combination of multiple conditions in bolstering DIE resilience. By grasping the substitution relationships and the complex nature of resilience, stakeholders can more effectively prioritize initiatives and allocate resources to safeguard DIES against disruptions, making the ecosystem more robust for future challenges.

## 5.2. Research Conclusions

Utilizing a case-study approach that examines digital innovation ecosystems across 31 provinces in China, this paper employs NCA and fsQCA within the TOE framework. The investigation explores the impact of antecedent conditions at the technological, organizational, and environmental levels on digital innovation ecosystem resilience, seeking insights into potential avenues for enhancements. The main conclusions are as follows:

Firstly, individual antecedents at the technological, organizational, and environmental levels alone are insufficient as necessary conditions for either high or non-high digital innovation ecosystem resilience. Secondly, this study identifies five configuration paths that enhance digital innovation ecosystem resilience: the digital technology-enabled organization–environment-driven type, the organization–environment dual-wheel-driven type, the digital technology-led environment-driven type, the technology–organization–environment trilateral type, and the pressure–organization-driven type. Thirdly, three configuration paths lead to non-high digital innovation ecosystem resilience, revealing an asymmetric relationship with configuration paths associated with high digital innovation ecosystem resilience. Lastly, this research highlights the potential substitution between antecedents at the technological, organizational, and environmental levels within specific conditions in configuration paths associated with high digital innovation ecosystem resilience.

## 5.3. Research Contribution

In terms of research design, this paper introduces the TOE framework to investigate digital innovation ecosystem resilience. By consolidating fragmented research on antecedent conditions, this study constructs a comprehensive theoretical model encompassing multiple antecedent conditions at the technological, organizational, and environmental levels. This approach not only advances the exploration of the antecedent conditions influencing digital innovation ecosystem resilience to a certain extent but also effectively responds to the call for attention to the multi-level factors influencing the smooth evolution and operation of innovation ecosystems [16]. Furthermore, the application of NCA



and fsQCA reveals complex causal relationships and provides insights into necessity and sufficiency. This addresses limitations in earlier research and contributes new empirical evidence regarding the mechanism of digital innovation ecosystem resilience.

In terms of research conclusions, this research identifies complicated causal linkages between many antecedent variables and digital innovation ecosystem resilience. It also identifies three types of potential replacement relationships, with R&D investments serving as a crucial component capable of increasing resilience by substituting or supplementing other variables.

#### 5.4. Recommendations

1. **Prioritize R&D investments:** First, prioritizing R&D investments is crucial to strengthening the “engine” of a system. As evidenced by its presence in four configurations of digital innovation ecosystem resilience, R&D investments is assumed to be universally pivotal. Policymakers should encourage collaboration and diversified-entity participation in R&D investments.
2. **Coordinate configurations:** Second, emphasis should be placed on recognizing the flexibility in attaining high resilience by combining technological, organizational, and environmental aspects. Strategies should be tailored to leverage an ecosystem’s specific strengths and address its challenges, whether through resource optimization, innovation-environment enhancement, or digital technology utilization.
3. **Learn from successful regions:** Third, emulating the successful strategies of resilient regions and seeking optimal paths to resilience are crucial. As regions with strong resilience frequently demonstrate unique configurations, western regions can learn from the successes of eastern and central regions, tailoring policies to their specific strengths and innovation environments to increase resilience. For example, Guizhou Province could leverage its geographical advantages to establish innovation bases like “China’s Tianyan” and “China’s Digital Valley,” thereby creating a unique edge for the development of its digital economy and the construction of an innovative environment. This strategic approach will contribute to the continuous enhancement of digital innovation ecosystem resilience.

#### 5.5. Research Limitations and Prospects

Firstly, the measurement of digital innovation ecosystem resilience in this paper is based on existing research [8]. However, the validity of this measurement framework has not been independently verified, indicating the necessity for future research to independently create an evaluation-index system tailored specifically to digital innovation ecosystem resilience. Secondly, this paper has a narrow focus on 31 Chinese provinces, lacking a global perspective that could enrich the findings. Expanding the scope to include resilience assessments at the city and county levels within China, as well as conducting comparative analyses with regions worldwide, could provide a more nuanced understanding of digital innovation ecosystem resilience. Furthermore, due to the limitations of the number of cases and the degree of detail, this paper selected five antecedent conditions based on the TOE framework. Future studies could further expand the conditions or combine them with other frameworks, such as the WSR methodology, to explore the influencing factors of digital innovation ecosystem resilience from different perspectives. Finally, given the dynamic changes and trajectories of antecedent circumstances and results, future studies could benefit from including a temporal dimension utilizing dynamic QCA [34].

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